RESEARCH PAPER

Scanning Hall Probe Microscopy (SHPM) Measurements of Crossing Vortex Lattices in (BSCCO) (2212) Single Crystals under Very High-Plan Fields

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ARTICLE INFO

Article History:
Received 29 June 2022
Accepted 24 September 2022
Published 01 October 2022

Keywords:
BSCCO single crystal
Crossing vortex lattices
Josephson vortices
Pancake vortices
Scanning hall probe microscopy

ABSTRACT

Semiconductor 2DEG with scanning hall probe microscopy Probe devices technique have been employed in the $Bi_2Sr_2CaCu_2O_{8+\delta}$ superconductor to explore for new phases of vortex matter in single crystals. Josephson vortices (JVs) and pancake vortices (PVs) are two orthogonal forms of flux structures that are created in the crossing lattices regime of these highly anisotropic superconductors when the magnetic fields are slanted (JVs and PVs). Studying the interaction of JV-PV material with extremely high in-plane fields has been done using SHPM technology. As a result of both in plane and out of plane fields, the spacing of JV chains has been measured. A surprising discovery is that the JV chain spacing is not simply dependent on the in plane field, as determined reliably, and that the functional anisotropic, γ_{eff}, is highly dependent on the out of plane field strength. Furthermore, the Josephson vortices stack spacing displays noticeable sawtooth-like oscillations as a function of the out of plane field while the in plane field is fixed. In extremely anisotropy cuprate superconductors with large Josephson vortex stack densities, these observations are revealing previously unknown features of crossing vortex lattics.

How to cite this article
Mohammed H A., Khalf A Z., Ali M J., Desoky W M. Scanning Hall Probe Microscopy (SHPM) Measurements of Crossing Vortex Lattices in (BSCCO) (2212) Single Crystals under Very High-Plan Fields. J Nanostruct, 2022; 12(4):959-967. DOI: 10.22052/JNS.2022.04.017

INTRODUCTION

Scanning Hall probe microscopy has been used to look at a single crystal sample of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO). The sample has a critical temperature (T_c) about (85.80.6) K. It has been a lot of work to study the vortex structure in anisotropic layered superconductors like $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) compounds in recent years. When the external applied magnetic field is inclined away from the C-axis, the different components of magnetic flux generate two different kinds of magnetic vortices: pancake vortices that stay in the superconducting planes and Josephson vortices that move between the superconducting planes. These two kinds of magnetic vortices are called pancake and Josephson vortices, respectively [1-3].

A. I. Buzdin and A. Yu. Simonov [3] thought that vortex chains would form in a tilted field because they were attracted to each other at long distances. They used the bitter decoration method to decorate $YBa_2Cu_3O_7$ samples and the scanning tunnelling microscopy to look at $NbSe_2$ samples

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[4].

Josephson vortices (JVs) and Abrikosov vortices (AVs) cross over each other in firmly anisotropic layered superconductors, where the magnetic field is sloped. This is because the line of PVs "Abrikosov vortices" and JVs communicate with each other. In this way, the parallel line of the PVs vortex is attracted and disfigured by JVs, therefore the JV stacks build up next to the PVs, forming a vortex row that is denser. Recently, scanning hall probe microscopy is also used to look at the vortex chains in BSCCO. These studies showed that the dense vortex chain state was stable even without a lattice and in a very sluggish magnetic field. Abrikosov PVs and JVs can only be found in strongly anisotropic layered superconductors in a tilted magnetic field because of their mutual attraction caused by the dislocation of PVs by JV supercurrents. This is called the "combined lattice" or "crossing lattices" regime [5]. The PV lines that are usually straight become attractive distortions around Josephson vortices. This leads to a mutual attraction and a build-up of PVs on JV stacks, which leads to chains with more PV density. After Buzdin and Baladie made their predictions, they also said that vortex chains would form in slanted fields because an appealing component of the interaction at long distances resulted them to form [3].

Grigorenko et al.[6] utilized SHPM to look at the interaction between crossing pancake vortex and Josephson vortex lattices in strongly anisotropic $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals with quenched disorder. They found that the PV/JV attraction is caused by small pancake vortex separations in the existence of Josephson vortex supercurrents.

Chains with more vortices were also found in Bitter decorations and magneto-optical imaging, and they were thought to be made up of lattices of pancake and Josephson vortices [7]. In this study, scanning hall probe microscopy (SHPM) was used utilised to look for new types of vortex matter in single crystals of the high-temperature superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ and to look at how the JV-PV in the single crystals changes with temperature and applied field [1,2].

MATERIALS AND METHODS

SHPM has been utilized to make two-dimensional maps of the local magnetic induction in BSCCO single crystal samples by using a hall probe that is only 0.8µm long. A GaAs/Al GaAs hetero-structure chip designs was made with electron beam lithography (EBL) by ELPHY Plus software and wet chemical etching. The contact materials: 60nm Ge, 130nm Au, 15-25 nm Ti and 150 nm Au, are evaporated sequentially in the same operation under high vacuum ($2x10^{-6}$ mbar) forming high quality metal layers. All chips are annealed under forming gas (95 % N_2 and 5% H_2) at 425^0C for 10

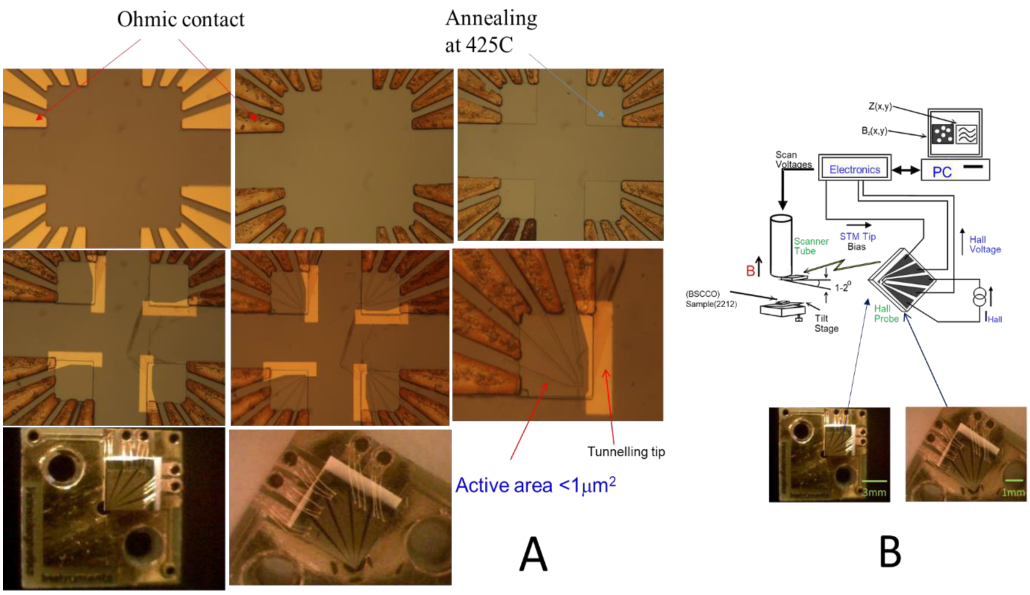

Fig. 1. (A) Fabrication of nanoscale 2DEG sensors by etching techniques for applications in scanning probe microscopy at 85 K. (B) Scanning Hall probe microscope (SHPM) with hall cross sensor device [9].

seconds in order to form good electrical contact to the 2DEG as Fig. 1(A). The sensor was made in this way. During the fabrication process all patterning and cleaning steps were performed in the same way as for the ohmic contacts except the resist spin speed was increased to 5000 for 30 seconds. The Tip was formed from a 10 nm thick layer of Ti followed by 50 nm layer of gold (Au). This is how the hall inquiry was made: It was about five micro-meters from the edge of an etched depth high point. It was then patterned with a thin layer of Au to make an STM tip that worked with the probe. A Hitatchi S4200 field-emission scanning electron microscope (SEM) connected to a Raith Elphy Plus pattern generator was used to write our Hall bar structures with an active size 0.8 µm,. Which used scanning hall probe microscopy (SHPM) technique at University of Bath / UK and the hetero-structure chip (sensor) has a critical temperature (T_c) about 85K as Fig. 1(B). For quick SHPM makes an angle with the sample plane of about 1 to 2 degrees. The STM tip is at the surface, and each 2D map of magnetic induction is typically divided into 128 x128 pixels, which are the same height as the STM tip. If more than ~10 images are needed to remove low-frequency noise from the Hall sensor, they can be averaging nearly frame by frame. Coils outside the cryostat made magnetic fields that were parallel and perpendicular to the sample plane. This meant that the field components could be changed individually [8,9]. They were made using the floating zone method [10] with crystals that were about 2mm x 2mm x 0.1mm in size. With scotch tape, the sample was cut in half, covered with a layer of Ge and Au, and then stuck to a piece of alumina sheet. Finally, a shiny and smooth surface was found. All nanoscale 2DEG sensors had made at Nanofabrication laboratory at Bath University but a single crystal sample of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) Commercially obtained from the University of Tokyo in Japan.

RESULTS AND DISCUSSION

A technique called SHPM has been used to look at how the magnetic field $H_{//}$ and the detachment of vortex chains, C_y, as Fig. 1(B) in highly anisotropic cuprate superconductors BSCCO single crystals work together. In this case, two separate sets of coils made fields that were parallel and perpendicular to the sample plane. This meant that one could change the field components. Normally, the spacing between Josephson vortex chains gets smaller with more $H_{//}$, and the density of chains rises until they begin to activity can cause when the separation for PVs is of order λ_{ab}. This is when they start to interact. Fig. 2 shows a set of SHPM images for a BSCCO single crystal as the in-plane field increases and the out-plane field stays the same (Hz=0.5, 5 and 7 Oe). It looks like they're decorated with yellow pancake vortex (PV). The spacing between the PVs gets closer as the magnetic field gets closer to the plane of the picture. The number of rows of interstitial PVs in between the Josephson vortex chains has a clear effect on how the Josephson vortex chains work. When there are small in-plane fields, the decorated Josephson vortices don't all line up perfectly. This is because the crystal has a lot of randomness and there are only a few pancake vortex (PV) that interact with each other, so there aren't enough pancake vortex (PV) to make full PV rows all the time. In a Josephson vortex stack, the in-plane field H_{II} has a big impact on how far apart pancake vortex (PV) on the stack are at equilibrium. The pictures show Josephson vortex (JV) chains with free pancake vortex (PV) in between them, as shown in the pictures Josephson vortex (JV) chains don't always line up next to each other in a straight line. The pancake vortex rows between chains disappear when the $H_{//}$ is high.

Fig. 3 shows the average spacing of JV chains. Error bars have been added to the figure based on how various JV chains look in the image. There is less spacing between JV chains when there is a strong magnetic field in the plane where they are. When there are no interactions between the JV lattices in question, Cy is predicted to be linearly related to $(H_{//})$ -Cy.$^{0.5}$ [2].

As the square root of the inverse in plane field ($H_{//}$) changes, the distance of the JV chains changes. In some fields, there are lines of free PVs between "decorated" JV stacks that have an exact number of lines of free PVs. N_1 shows where we saw the structure with only one chain of free PVs at $H_{//}$ **=** 300 Oe for Hz = 10 Oe. This is close to the start of the first peak in Fig. 3. N_2 is a structure with two rows of free pancake vortex that was found at $H_{//}$ **=1**50 Oe. It is near the start of the second peak. On the surface, there could be a never-ending number of free PV lines, which free pancake vortex rows (i.e., 0≤N≤∝).

Calculated: The slope of C_y against H-0.5 has been used to figure out how big a difference there is between the slope and the equation below [11].

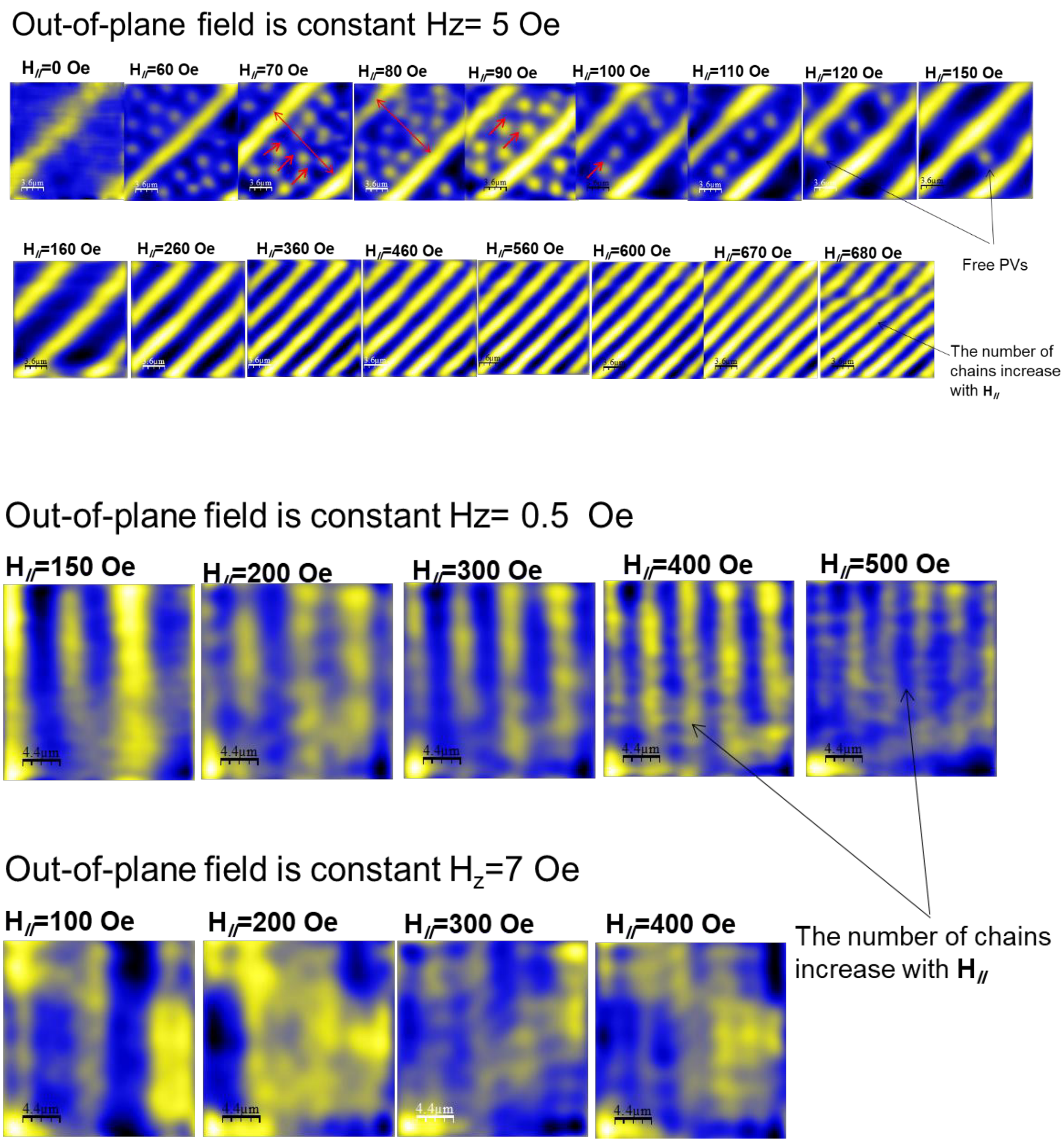

Fig. 2. "SHPM images showing that the distance between chains decreases with increasing in-plane field for fixed out-plane-field at 85K. Fluctuations in the JV chain spacing as a function of the $(H_{//})^{-0.5}$ is observed. The image size is ~20x20 µm^{2}.

$$C_y = \left(\frac{\sqrt{3}\ \gamma_{eff}\ \Phi_\circ}{2H_{//}}\right)^{0.5} \qquad (1)$$

"where, C_y is the mean separation of JV chains".

Fig. 4 shows example images for $H_{//}$ = 315 Oe and H_z = 3.4 Oe with and without dithering. Clearly a more homogenous vortex distribution is achieved after dithering the in-plane field.

Fig. 5 shows the estimated values of effective anisotropy, γ_{eff}, as a function of Hz. The decline in γ_{eff} with Hz is very smooth, and it does not appear to be especially sensitive to dithering circumstances.

The single solid curve shows theoretical effective gamma predictions based on Koshelev [2] theory. It is provided by:

$$\gamma_{eff} = \gamma \left(\frac{B_\lambda}{B_Z\, C}\right)^{0.5}$$

$$B_\lambda = \frac{\Phi^\circ}{4\pi\lambda^2} \ln\frac{\lambda}{r_w},\ (r_w \sim 270\ \text{nm}), \qquad (2)$$

$c = 3.1$ and B_Z (H_z) is an out-of-plane field

The outcome of a computation that considers the influence of PVs on the JV lattice. PVs effectively

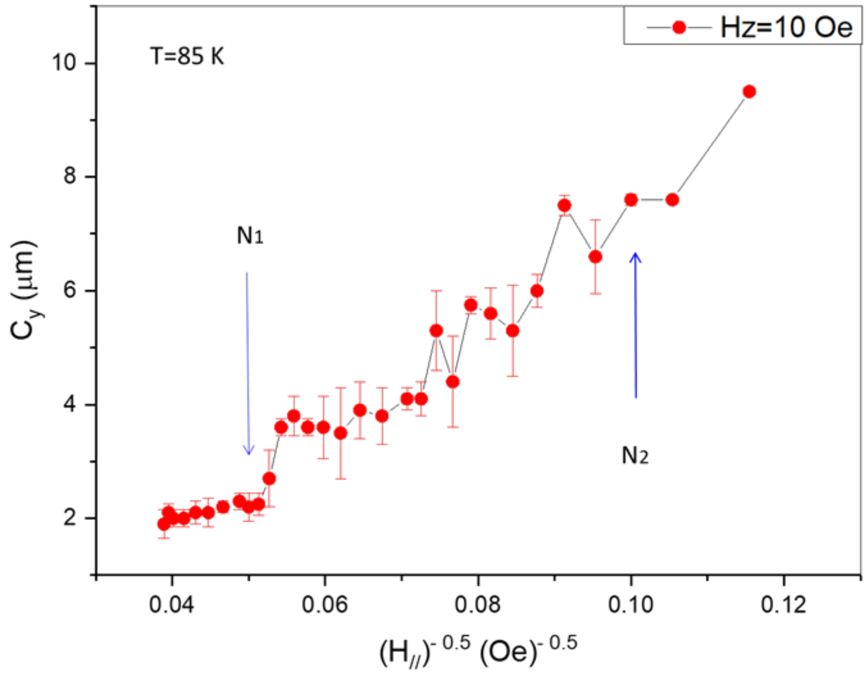

Fig. 3. Plot of JV chain spacing of free PVs for H_z=10 Oe as a function of $(H_{//})^{-0.5}$".

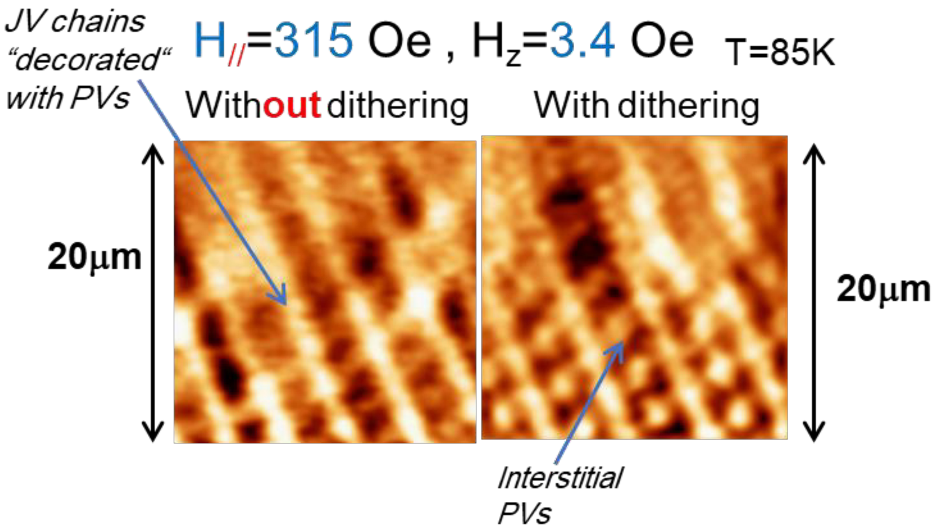

Fig. 4. "The out of plane field dither was 3 Oe at 10Hz with the same exponential decay. Vortex distributions at T_c = 85K and fields of $H_{//}$ = 315 Oe and H_z = 3.4 Oe without and with dithering".

minimize C_y. gamma is the anisotropy of the JV lattice without the PVs, and it's an inherent value here.

It has been shown that high-resolution SHPM may be employed at large fixed values of $H_{//}$ for studying vortex matter in BSCCO as a function of frequency Hz. Out of plane field is predicted to have no effect on the spacing in this situation. This, unfortunately, does not appear to be the case. Chain separation is significant in Fig. 6, with free pancake vortex appearing in between the chains, making it easier to see low and high in plane fields.

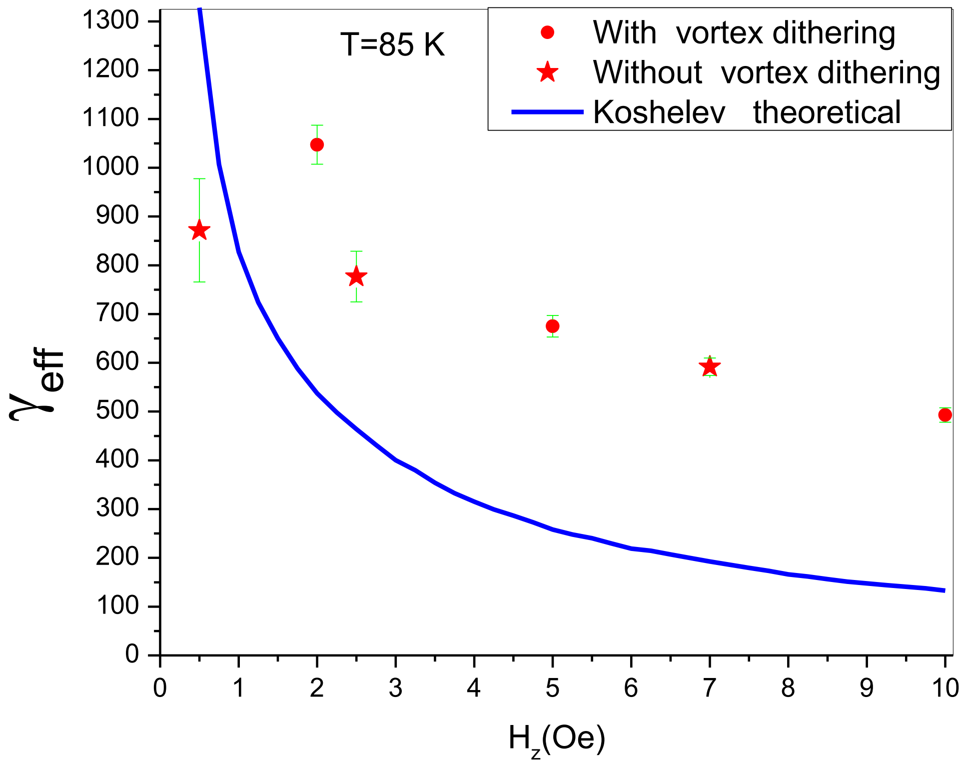

Fig. 5. Estimated effective anisotropy as a function of out-plane field. Solid circles represent date captured with dithering, while stars were taken without dithering. The effective Gamma curve is plotted by Koshelev's theory with =1715" 2.

This, nevertheless, does not appear to be the case. Family photos at low (-300 Oe) and high fields (650 Oe) are shown in Fig. 6. blue arrows represent the initiation of rows of free PVs between JV chains. The chain spacing reduces as the out of plane field (Hz) strength increases, which is extremely startling and unusual. As the number of rows with free PVs rises, we see irregular fluctuations in the chain spacing. There are no rows of free interstitial pancake vortex created in the JV chains when in plane fields ($H_{//}$) are high enough (e.g. 650 Oe), the out of plane field (Hz ~28.3 Oe) to surpass saturation PV density of the JV chains.

At high in-plane fields and gradually increasing out-of-plane fields, the structure of JV stacks 'decorated' with PVs were investigated. Although part of the rounding may be due to a high background noise level, in Fig. 7 (a) the JVs' low-frequency profiles appear to be roughly triangular and appear to have a more rounded shape at high frequencies. However, the chain amplitude reduction might be partially ascribed to PV chain kinking, which causes the chains to widen (in combination with the fact that the chain spacing gets a bit smaller at higher out of plane magnetic field (Hz) as well). Fig. 7(b) depicts the widening of JVs as the high in-plane field increases at T=85K. Saturation values for $H_{//}$ > 400 Oe may be clearly observed in the greyscale, which begins low and then progressively increases to its climax. Figs. 7 (b) and 7 (c) indicate that the greyscales (shown in green) peak immediately before the first interstitial PV emerges (c). Because pancake vortex has the greatest average spacing at this field, the grayscale is much longer at the lowest Hz.

Pancake vortices in neighbouring layers interact through the magnetic field associated with the vortices in layered superconductors under slanted magnetic fields. This means that the tilt of a vortex line can only be achieved by creating a collection of kinks between the layers of pancake vortices. The kink in the a-b plane [12] is nothing more than a sliver of Josephson vortex. Pancake vortices have little effect on the structure of JVs when the c-axis fields are low and the anisotropy is large. When two pancakes are placed next to one other, they

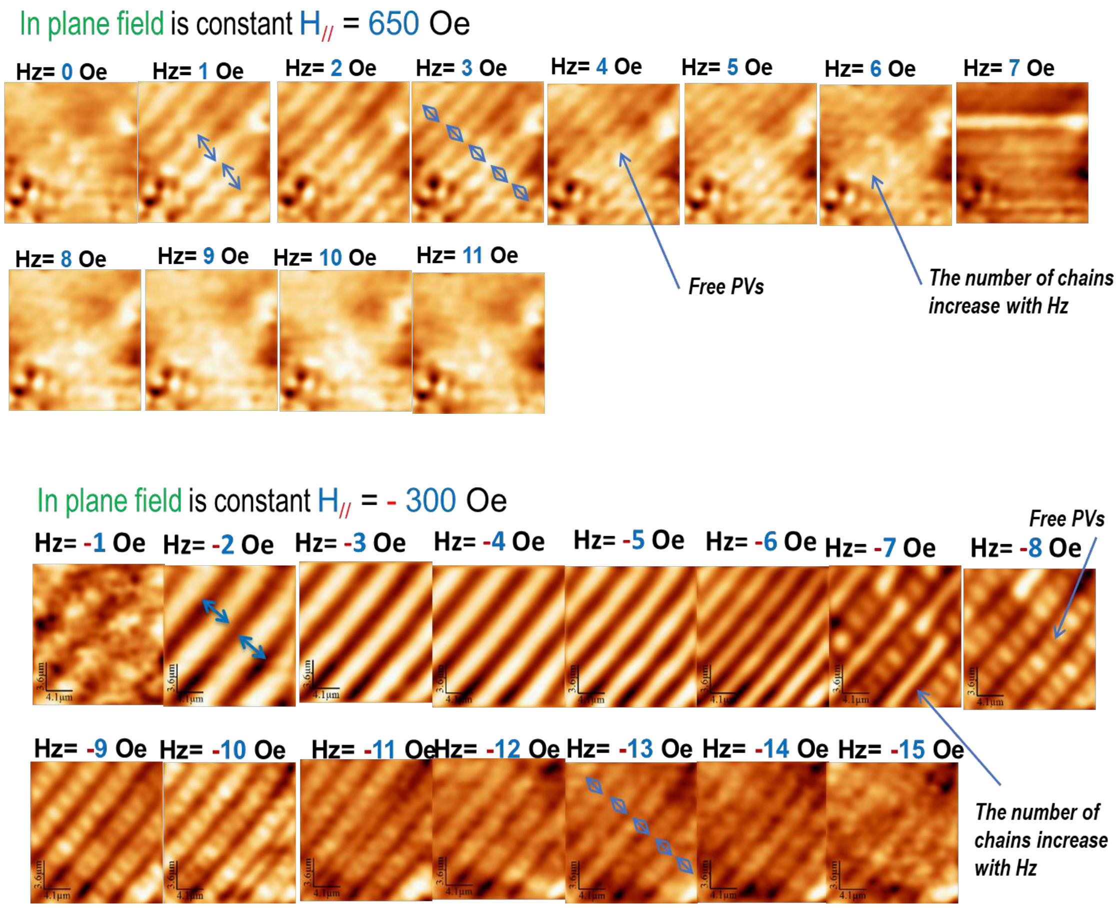

Fig. 6. SHPM images in a BSCCO single crystal as a function of H_z at two fixed values of $H_{//}$ at 85K. The image size is ~20x20 µm$^{2''}$.

create what is known as a mixed chain-lattice state because of their limited contact energy (the crossing energy). As a result, in-plane fields up to 750 G were used in conjunction with applied c-axis fields in the Hz ~0.5–10 G range to examine a hitherto understudied region. Few researches have used SHPM to examine BSCCO lattices with a single vortex resolution, in particular, crossing lattices.

The London ratio is primarily responsible for the lattice structure of a single chain ($\lambda = \lambda_{ab}$) and Josephson ($\lambda_f = \gamma_s$) lengths, $\alpha = \lambda / \lambda_f$ with γ being the anisotropy parameter and *s* being the CuO_2 bilayer spacing. The ratio determines the internal structure of an isolated interaction chain, and in two specific circumstances, this structure is quite simple. Josephson vortex and pancake vortex stacks form a 'crossing' array at tiny. A substantial portion of it is made up of "tilted" pancake vortex stacks [13].

Koshelev [2] reported that $\boldsymbol{\gamma}_{eff}$ depended on out of plane field H_z (or $B_z = \boldsymbol{\mu}_0 H_z$) as shown in equation 2. Here B_λ is given by:

$$B_\lambda = \frac{\Phi^\circ}{4\pi\lambda^2} \ln \frac{r_{cut}}{r_w}; \text{ where } r_{cut} = \min(\alpha, \lambda) = \lambda$$

This predicts $_{eff}$ for the JV lattice depends on $(B_z)^{-0.5}$ (or $(H_z)^{-0.5}$).

As a consequence, the variety of measured data of γ_{eff} spans from 495 -1150 and weakly changes depending on vortex dithering. Fig. 5 depicts the effective gamma, which according to Koshelev's theory should behave in a manner that is qualitatively comparable to the one shown here. In the absence of interactions with PVs, the anisotropy of the JV lattice has an inherent value of.

The two characteristic regions in Koshelev's phase diagram are observed in our experiments as illustrated in Fig. 7:

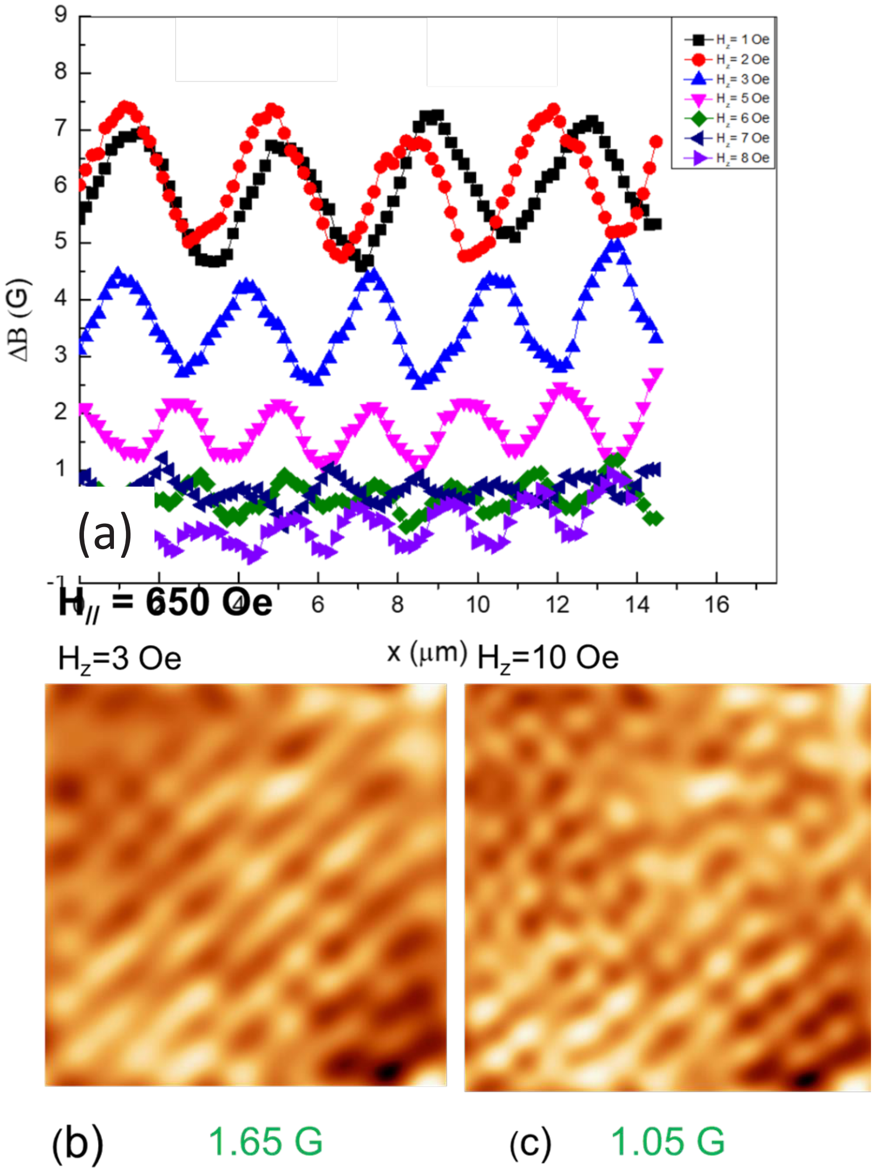

Fig. 7. (a) Huddle of the average JV chain profiles at $H_{//}$=650 Oe and various values of H_z (vertically offset for clarity). SHPM images in a BSCCO single crystal of possible PV structures at low (b) and high (c) out-of-plane magnetic fields which it shows the number of JVs, in white. The image size is ~20x20 μm². Image greyscales are recorded below in green".

1) Streaks with very little power show where the Josephson vortex chains are at very low out of plane magnetic field. This is like the slanted chains in Fig. 7(b).

2) Very powerful, well-resolved crossing pancake vortices are detected along the Josephson vortex chains as Hz is raised to ~0.5-1Oe. Fig. 7 shows pancake vortices (PVs) with S-shaped kinks crossing each other when the stack contacts each other (c).

These phases are described qualitatively as follows. Tilted chains with straight and inclined pancake vortex lines are formed when the C-axis field is relatively tiny. These low density, slanted chains, though, undergo a first order phase shift when the C-axis field is increased. The pancake vortex density increases dramatically during this transition. Second order transitions occur when these crossing chains convert back into slanted chains as the field increases.

There is not yet a theory that can explain how the oscillations in C_y(Hz) work, but Alex Koshelev [13] is starting to work on this. But even so, a qualitative description looks like this: System: There are two ways that the system can handle more pancake vortices as the Out of plane magnetic field goes up. In the first place, you can reduce distance between JVs (C_y) and increase the chain density (($\propto 1/C_y$). In a way, this is a constant change that trades off a decrease in the energy of the PV-PV interaction (on the JV chains) for a decrease in the energy of the PV-JV interaction. Second, you can make rows of free PVs between the chains. This occurs when it takes more energy to put some other Josephson vortex on a chain than to make a free interstitial Josephson vortex. In practice, it looks like there is a lot of competition between these two mechanisms. People who do experimental studies say that when they raise the out of plane magnetic field, the distance between JVs (C_y) first drops, but then unexpectedly opens back up when the first PV row comes up. Because there are interstitial PVs, clearly the system moves extra PVs from the Josephson vortex chains to make room for them. This makes it possible to move again the JV stacks away from each other (and decrease their density). A "sawtooth-like" dependence of distance between JVs (C_y) on out of plane magnetic field is formed after this. Distance between JVs (C_y) starts to drop again until the second row is formed, and so on, until the third row and so on.

CONCLUSION

SHPM was utilized to look at how JV and PV matter worked together in very anisotropic $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) solid dispersion in very strong in plane fields. JV stacks are close together at quite high $H_{//}$ values, so the PVs trapped on the chains next to each other have a lot of contact. Here, the distance between each Josephson vortex stack is based on both in and out plane fields (PV density) instead of just on $(H_{//})^{-0\ 5}$ as is generally assumed. The structure of Josephson vortex stacks that were "decorated" with PVs at very high in plane fields, while the out plane field kept going up over time. In our experiments, we have looked at the range $0.50 \leq \alpha = \lambda_{ab}/\gamma_s \leq 0.65$ in the fields we work in. These measurements are giving us unparalleled information about the properties of crossing vortex lattices in cuprate superconductors with high Josephson vortex densities, which are very different from cuprate superconductors in other ways.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

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